To Study the Influence of Frictional Conditions and Die Land Length on Component Error and Die Deflection in Cold Extrusion by Finite Element Analysis

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Abstract

Component errors and die deflection and hence the quality of the extruded components are directly influence by the generated temperature due to friction during the process, the elastic and plastic behavior of the component, die geometry and billet and die material. Finite element simulation is conducted to study the influence of Die Land Length (DLL) and frictional conditions between the die inner surface and billet outer surface, on the component errors and die deflection during forward extrusion by using elastic plastic considerations. The simulations show that the dimensions of the work-material and die are affected by increase in temperature due to the change in frictional condition during process and die-elasticity during both, loading and unloading of the die. Increasing the punch pressure and hence friction between the billet and die results in larger radial deflection of the die during extrusion (loading), which results in larger values of component errors in extruded material. The elastic contraction of the die during the punch retraction (unloading) reduces due to high level of friction and more amount of heat generated; hence larger form errors are sustained after unloading. The plastic deformation of the billet material remaining in the die is influenced by the temperature variation in the billet as well as in the die during unloading phase, this plastic deformation of the billet material due to the temperature variation has a significant role in the overall form error of the component, hence the quality of the extruded material. Although, the die land length does not have significant effect on bar temperature, die stress and die deflection but it has a significant effect on component error which reduces with increased die land length.

Keywords

Die Land Length; Friction; FEA; Component-errors; Die-deflection

Introduction

Extrusion is the process by which the block/billet of metal reduces in cross section by forcing it to flow through the die orifice under high pressure. In direct cold extrusion, mechanical properties of the material, frictional condition at the tool workpiece interface, geometric profile of the die, extrusion speed and extrusion ratio are among the important parameters that significantly affect the desired characteristics of the product [1]. Optimization of these parameters in the light of die design as well as process design has been the most important tasks that have attracted the attention of many researchers. In the process design of extrusion, homogeneous deformation, minimization of load and energy, minimization of tool wear and control of microstructure of the product are some of the important points that should be considered

The behavior of material in cold extrusion process depends not only on their mechanical properties but also on the conditions under which extrusion deformation occurs, such as die geometry, temperature, strain and strain rate etc. According to [2] both the state of stress and the temperature are complicatedly related to the various extrusion conditions, including initial billet temperature, ram speed, reduction ratio, and friction at the interfaces. According to Shivpuri the state of stress depends on deformation resistance of the billet material, die land length as well as thermal characteristics of the billet material and the tooling [3]. They suggested some empirical relationship to find out these parameters and concluded that the practical means to accurately measure the form errors, stress, strain and temperature is yet quite limited.

In the process of cold extrusion, the material flow plastically and the ability of material, particularly metals, to undergo plastic deformation rather than fracture is an invaluable property. This would result in

increase in their mechanical properties such as hardness and tensile strength and induce residual stresses within the part and can only be relieved by an appropriate heat treatment process [4]. Moreover, strength and hardness of the metal are increased with a corresponding loss in ductility as a result of distortion or fragmentation of the grain structure occurs which results in component errors, poor surface quality and surface tearing.

During the process of extrusion, the pressure is minimum at the start and there is a rapid increase in pressure near the end of extrusion. This, sometimes, results in a defect known as cavity formation at the centre of the billet [5]. As the pressure increases, the cavity increases in diameter and depth and hence it may cause the occurrence of central bursting. The occurrence of central burst in cold extrusion affects the surface quality of the extruded product and results in component error, Avitzur has established a criterion to predict the central bursting defect for conical dies using upper bound method [6].

The plastic deformation of the work material and the interfacial friction between the billet and the die generate temperature which will influence the geometrical accuracy of the extruded part. The influence of die land length and transition radii on the geometrical accuracy of the extruded part has been investigated by Pyzalla for the cold extrusion process using a finite element analysis [4,7] and found that the transition radii does not has a significant effect on component errors and die deflection. The forming of complex profiles has been attended in industry by a series of iterative forming trials and each trial enabling reduction of a proportion of the form-error. There is no prescribed method for the systematic exclusion of form-errors in the component to improve the quality of the product.

The influence of the die geometry and die-deflection on the dimensions of the extruded material was investigated [8], and a new die structure has been proposed to compensate radial dimension errors of the extruded material. This analysis was based on the slab method for calculating extrusion pressure and process temperature. Also elastic finite element analysis was carried out by Osakada to compute the deflection of the die at the exit by considering only loading cycle [9].

It is also necessary to study the unloading behavior of the die and work material because it will constitute a significant proportion of the overall form error and temperature variation after extrusion. Considerations for the elimination of form errors in conventional extrusion are more complex since the work-material remaining in the die is subjected to high deformation temperature and pressures during both, tool extraction and component ejection.

Therefore, to ensure the quality of extruded products, one need first to understand the process in relation to the external and internal process conditions and then to optimize the process. In conventional studies on the extrusion process, material flow is experimentally determined. The prediction of metal flow, heat generation and heat transfer during severe deformation process is becoming more of a current trend in the industry. The numerical techniques significantly reduce the costly time-consuming trial and error experiments. At present, FEM simulations are gaining momentum in simulating the temperature generation during the complex metal forming processes.

The accuracy of the process and net shape manufacturing is the present demand of the world and cold forward extrusion is a near-net shape manufacturing process. The effects of various parameters such as coefficient of friction (frictional condition) and temperature, flow of material (die land length), defects in extruded material, component and die errors, and optimization of die design are some of the important parameters, which attracted the researchers on forward extrusion. Kobayashi [10] and others have studied and got a more comprehensive understanding of the mechanism of extrusion and better design of tools. The prediction of component error due to the temperature generated during extrusion and surface fracture by Clift [11], has contributed to the improved use of the process.

Some studies have been addressed on the quality of the extruded material, which arise because of the variation in coefficient of friction during the process and deflection of the tool. Component errors and die deflection could result from machine and tool dependent errors in cold extrusion. Several studies refer to component-errors which originate from the behavior of the machine tool and process parameters. Investigation of the loading history of the machine-tool system [12] with a view to defining its response during forming operations would enable an appreciation of the factors which influence component form-errors and hence quality of the product. The interrelationship between billet and die-behavior, and the resulting effect on the final geometry of the

component has, however, not been assessed completely.

Variation in frictional conditions causes the variation in temperature, which would result in extrusion defects such as form error in the billet and the deflection in the die. Form errors in component during plastic deformation of material may originate from the deflection of the machine and the elastic deformation of the die, which is not possible to eliminate completely. Some research works by Balendra [13] have been conducted to investigate the influence of machine and die elasticity on component geometry using the combination of elastic and plastic finite element simulations. Error analysis and evaluation systems of errors were developed for nett forming with a view to improving efficiency of nett forming manufacturing. It was concluded that the errors resulted from the die elasticity were compensated by modifying both the geometric and physical conditions of the extrusion process. The frictional conditions can be improved and the temperature generation during extrusion process can be reduced by the application of various lubricants. Some researchers [14, 15] have attempted to investigate the effect of various lubricants at the die billet interface on the punch load.

Frictional condition between billet and die and the influence of shear friction factor in the process design of cold extrusion are some of the crucial parameters and should be accurately described, since it directly affects the quality of the extruded material, material flow inside the die, forming load etc. in extrusion. The constant shear friction model is the most widely used to quantitatively describe the global average friction condition in metal forming operations [16]. Therefore, the shear friction factors must be determined based on lubrication conditions for the constant shear friction model to be used effectively. The ring compression test has been widely used to find out shear friction factor by many researchers [17, 18, 19]. However, due to its simplicity the shear friction factor obtained from the ring compression test may not be always suitable for actual metal forming processes. Finite element analyses were performed with varying shear friction factor [20] and they observed that the higher values of shear friction factor at the punch as compared to that at the die during numerical simulation of extrusion process produced better results.

Other than the process parameters, the surface quality of cold extruded parts is also affected by geometrical parameters of the die such as die land length, die angle, reduction ratio, loading rate etc. Experimental investigation has been made to determine the effects of these parameters on the quality of cold extruded parts, extrusion pressures and flow pattern for both Aluminum and Lead [21]. They determined some empirical equations to assess the effect of the aforementioned extrusion variables on the extrusion pressure.

Many researchers investigated the influence of geometrical characteristics such as die diameter, die land length etc. on the power required to extrude the material. The metal flow and power required in cold extrusion are greatly influenced by the extrusion die geometry, frictional condition at the die-billet interface and thermal gradient within the billet [22, 23].

The geometrical features of the die land are critical in obtaining defect free cold extruded parts. As the die land length directly influences the amount of friction at the die billet interface, this geometrical parameter is used by extrusion die designers to control the metal flow through the die. Appropriate die land length will allow uniform distribution of residual stresses in the extruded part as it emerges from the die. Various proposals have been made [24, 25, 26], to provide a numerical basis for the design of the die land parameter.

With the recent increase in demand for accurate forming, necessity for more efficient design has become an important issue. Instead of using traditional design methods based on experiments, experience and trial and error methods, the use of computers in design of metal forming operation has become widespread to reduce both consuming time and cost. As such, the numerical analyses of metal forming processes based on finite element method (FEM) has become a common tool in the process design and die design stages of product development.

Finite element technology is widely used in numerical simulation of metal forming processes. It provides an important means for optimization of metal-forming processes, but frictional boundary condition treatment is very difficult between die and billet during FEM simulation of metal-forming processes. A model has been presented [27] for dealing with frictional boundary condition and lubrication process during cold extrusion.

It is established from the review of literature that the various process and die parameters influence the punch load, power required for extrusion, stresses in

bar and die and the temperatures in the bar and die. These in turn, affect the quality of the product. It is very essential for a process designer to analyze the effect of process and die parameters on these to avoid the costly trial-and-error procedure commonly adopted.

The review of literature has shown that the theoretical methods such as upper bound analysis are quite limited in their application. These can, perhaps, give the punch load accurate enough for estimation purposes but can not provide complete answers to the problems of the process designer. The physical modeling, which has been tried by few researchers, can only lead to a better visualization of the metal flow in the deformation process but is similarly limited in its versatility. Taking a general view of the present state of the art in terms of numerical modeling it appears that the finite element method is the most suited for the analysis of the extrusion processes.

There has been a number of studies on the optimum die design and effect of process variables on die deflection and component error. With the recent trend in the industry for nett forming, it is important to minimize the component error so that the final product is very near in shape to the desired shape. The literature has shown some attempts to apply the finite element method towards this end. But, the reported studies are isolated studies and not exhaustive.

It is well known that the accuracy of finite element simulation depends upon the finite element formulation and type of modeling employed. The accuracy of finite element simulations also depends on the type of elements employed and quality of the description of boundary conditions at various interfaces (billet outer and die inner surface). Which modeling is best suited for extrusion analysis? Which type of element is best suited? The reported studies have not tackled these and similar issues.

The reported research considers the influence of variation of temperature due to variation in frictional condition on the quality (form error) of the extruded material. The influence of die geometry (die land length) and die-elasticity on component error and die deflection during extrusion of solid billet is also discussed. Using FE analysis, a detailed analysis for the effect of coefficient of friction and die land length on the deflection of the die as well as component error have been carried out. Using the commercial package ABAQUS (elastic-plastic formulation), a non-steady state process analysis was carried out to define the elastic and plastic deformation characteristics of the work material and die. The influence of variation of temperature on the quality was investigated by considering different process conditions, such as die/billet material interfacial friction, billet and die material properties, punch loading and unloading.

Process Description

Fig. 1 shows the geometry of the billet and die for forward extrusion. The process parameters are billet diameter 40.0 mm, extrusion ratio is 1.78, internal diameter of the die 40.0 mm, die half angle is 22.5° and transition radii are *R1*=*R2*=10 mm on the die. The die land length (*a*) is 3 mm. The dimension of the extruded material is prescribed by the extrusion ratio. It is, however, only a nominal dimension since the actual dimension of the extruded material is dependent on the deflection of the die.

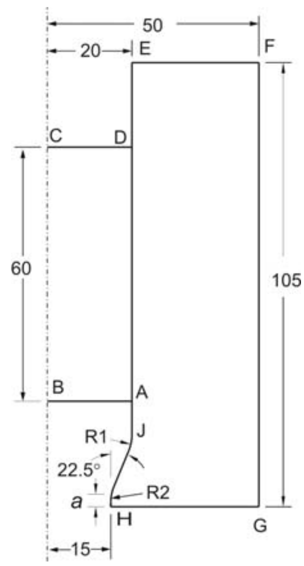

FIG. 1 BILLET AND DIE GEOMETRY

During extrusion, the die expands radially, the extent of the expansion depends on the structural properties of the tooling. The pressure on the working surfaces and quality of the extruded material would be a function of several factors such as friction, temperature and the material properties of the billet. Further, the extruded material recovers elastically outside the die at a room temperature, thus acquiring a variable dimension. The billet material contained in the die undergoes a sequence of deflection and deformation because of the variation in temperature during extrusion step and cooling step. Initially, the temperature rises and the die expands radially in response to the increasing extrusion pressure. At the stage when the punch is retracted; the billet material is compressed by the elastic contraction of the injection

chamber [28, 29]. The billet material is also contracted because of fall in temperature, when the punch is retracted. This may result in plastic deformation of the billet material. The subsequent ejection would also cause elastic deflection of the component, when the billet temperature falls to room temperature.

FE Simulation

The simulation of extrusion as a non steady-state process requires the use of a Finite Element Analysis software which has the capability of dealing with large sliding-contact boundary problems. Abaqus satisfies this requirement [30]. Abaqus provides sliding contact elements which enable the simulation of large sliding contact between deformable bodies, the Lagrange multiplier method is used for contact constraints. Element type CAX was used for modeling both the billet and die. The initial meshes for the FE model of the billet and die when they are in contact as shown in Fig. 2.

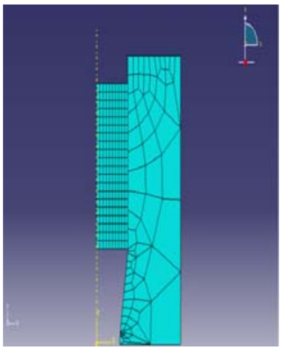

FIG. 2 MESH MODEL

The required coupled solution in which the elastic and plastic behavior of the material, heat generation and transfer and the temperature as well as dimensional variations of both the forming tool (die) and the component (billet) can be simulated simultaneously in a finite element analysis software Abaqus. In this simulation, the incremental plasticity theory and Von Mises criterion have been used to analyze the plastic flow of the material. Also the heat generation as well as temperature rise in component and die has been considered. Whereas the recoverable deformation of the component and the die was described using a linear elastic model. Contact between the deformable billet material and die was modeled using a contact pair approach, in which interfacial friction, heat generation and heat transfer were defined. During extrusion, the punch displacement was accomplished by prescribing displacements of the nodes at the top surface of the billet material. The tool velocity was modeled by defining different contact times during extrusion. At the end of extrusion, retraction was modeled by removing the contact constraint. During cooling, the contact constraint between the component and die interface was removed and the component was released from the container. The component and the die were then allowed to cool by heat diffusion via film conditions and cooling time. The mechanical properties of the die material i.e., density, Young's modulus and Poission's ratio are 7865 kg-m^{-3}, 210 GPa and 0.3 respectively and the thermal properties of the die material i.e., specific heat, expansion coefficient and thermal conductivity are 460 J Kg^{-1} K^{-1}, 1388×10^{-5} K^{-1} and 50 W m^{-1} K^{-1} respectively. The billet material has been considered as low carbon steel (C15). The mechanical and thermal properties of billet material are density=7833 kg.m^{-3} Young's modulus=210 GPa, Poisson's ratio = 0.3, specific heat=465 J.kg^{-1}K^{-1} thermal expansion coefficient = 1.474×10^{-5} K^{-1}at 20^{o} C.

The flow stress and thermal conductivity of billet material are temperature dependent, and are as shown in Table 1.

TABLE 1 TEMPERATURE DEPENDANT PROPERTIES OF BILLET MATERIAL

Temperature (^{o}C)	Flow stress (MPa)	Thermal conductivity (W.m^{-1}.K^{-1})
20	750 $(\varepsilon)^{0.01}$	54
100	720 $(\varepsilon)^{0.05}$	52
200	740 $(\varepsilon)^{0.20}$	48
300	780 $(\varepsilon)^{0.15}$	45
400	740 $(\varepsilon)^{0.06}$	42

The billet and the die were assumed to be in initial contact without clearance. The FE models with different process conditions were established for studying the variation in temperature during extrusion process. The influence of material property (die elasticity) and friction on dimension variations (quality) of the component and the die was also studied.

All models to be compared were simulated for the same punch displacement. The work-material was assumed not to have a displacement relative to the punch, the implication being that all nodes at the interface had the same displacement; the movement of the punch was simulated by prescribing a displacement condition at the top surface of the billet.

Simulation Cases

Various finite element simulations have been carried out, to study, the effects of interfacial friction between billet and die and die land length on dimensional variation of billet and die. The various simulation cases are shown in Table 2.

TABLE 2 VARIOUS SIMULATIONS

Simulation No.	Coefficient of Friction	Die Land Length (*a*) (mm)	Transition Radii *R1* & *R2* (mm)
1	**0.03**	3.0	10.0
2	**0.04**	3.0	10.0
3	**0.05**	3.0	10.0
4	0.04	**3.0**	10.0
5	0.04	**5.0**	10.0
6	0.04	**7.0**	10.0

The nominal diameter of the extruded bar, as prescribed by the die geometry should be 15 mm, but the actual diameter of the bar after extrusion is not exactly the same as the nominal diameter. The difference in actual diameter of the bar after extrusion and the nominal diameter is defined as the component error. This error results from the elastic deformation of die, the elastic recovery of the extruded billet and thermal contraction subsequent to the extrusion. This error depends upon the material properties of the bar and the die also on the die parameters.

In these simulations CAX4T element and M10-20 (equally spaced 10 elements in x-direction and 20 elements in y-direction) mesh density have been employed. The results are presented and discussed in the subsequent sections. The results are taken at the various node locations on the bar and the die after extrusion. The scheme of numbering of node locations is shown in the Fig. 3.

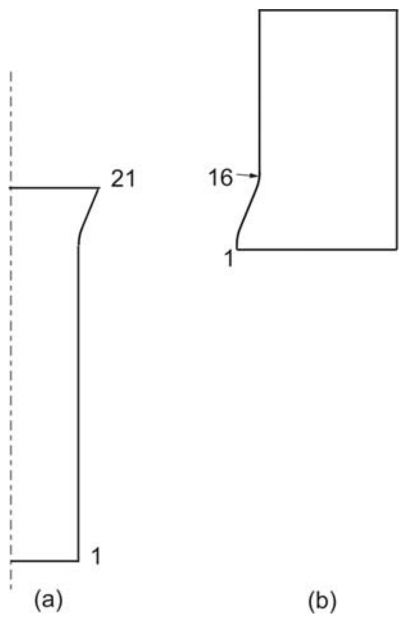

FIG. 3 NODE LOCATIONS ON (A) BAR (B) DIE

Results and Discussions

Effect of Coefficient of Friction

The effects of change of coefficient of friction (COF) on extrusion process have been studied by considering the die land length as 3 mm and transition radii *R1* and *R2* as 10 mm. The Fig. 4 (a) shows the plot of Mises stress in the bar and the die at the beginning of extrusion and the contour of temperatures are shown in the Fig. 4(b).

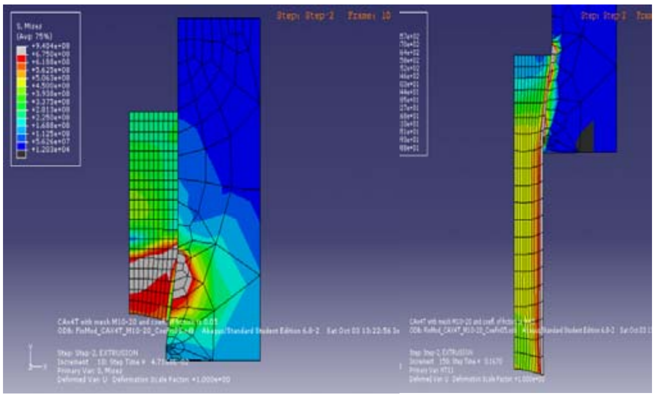

FIG. 4 (A) MISES STRESSES AT THE BEGINNING OF EXTRUSION, (B) TEMPERATURES AT THE END OF EXTRUSION FOR DIE LAND LENGTH=3 MM, COF=0.05, R1=R2=10 MM

The results regarding the effect of COF on punch force, component error and die deflection are presented in the following.

Effect of COF on Punch Force

The punch force increases as the COF increases as shown in Fig. 5. This is expected as the increased COF requires more energy to be spent in overcoming the frictional resistance. The increase is almost linear.

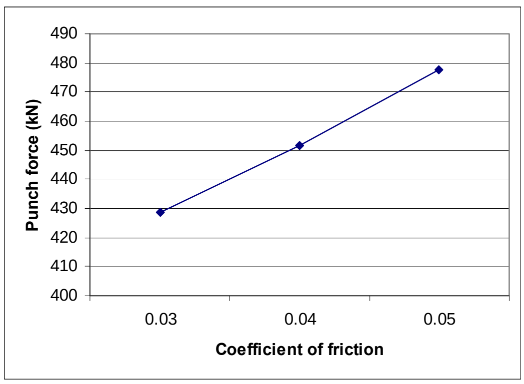

FIG. 5 EFFECT OF COF ON PUNCH FORCE

Effect of COF on Component Error

The component errors at various locations computed from finite element simulations are shown graphically in Figure 6. Since component error is meaningful only for the portion of the extrudate completely outside the die, the error is shown only upto the node location.

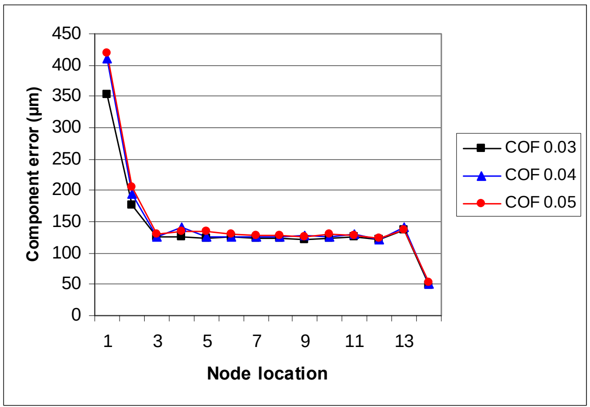

FIG. 6 EFFECT OF COF ON COMPONENT ERROR

Results show that the component error for COF 0.03 is the highest for the initial or outer most location of the bar. The error reduces sharply and varies slightly along the length of the extrudate. At locations close or inside the die the component error is very low (50 µm), because of the restriction offered by the die geometry as shown in Fig. 6. The variation pattern of the component error for different COF at the various node locations is same, with a slightly higher component error for higher COF. The maximum component error for COF 0.03 is 353 µm and for COF 0.05 is 420 µm with 16 % variation

As COF increases, "out of smoothness" it offers more friction between the interacting surfaces and flow of the material is not smooth. During extrusion, the material flows through the die and if the friction is more, it will produce more heat and hence the temperature of the material inside the die rises. The softening effect of the material takes place at the elevated temperature and material deforms easily, therefore, the component error is more. Hence, as the COF increases, this will results in more component error as shown in Fig. 6. Except a few node locations, the component error is around 125 µm for most of the node locations.

Effect of COF on Die Deflection

As the extrusion process is carried out, the die deforms radially because of the punch force. After extrusion the die contracts elastically. The elastic contraction is restricted by the material remaining in the die. Since this effects the final error of the product, the die deflections are also included in this study. The difference between the original internal diameter of the die and internal diameter of the die after extrusion is termed as die deflection. This is calculated by the difference between the original X coordinate and deformed X coordinate of the die after extrusion at various node locations on the die. The results are taken at the various node locations of the die and shown graphically in Fig. 7.

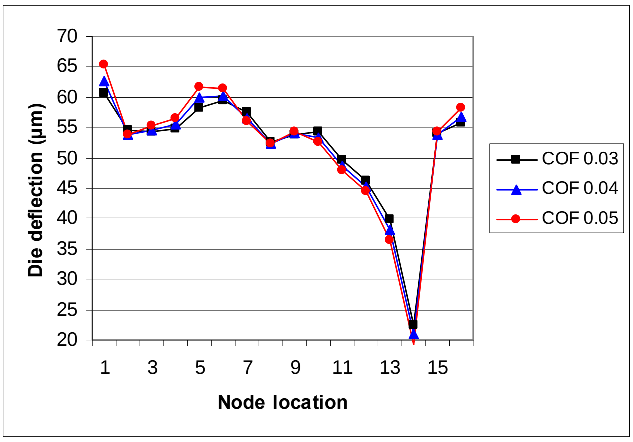

Fig. 7 Effect of COF on Die Deflection

The die deflection decreases as the node location increases except for a certain portion around the lower transition radius where it increases sharply. The die deflection is more in the lower part of the die due to presence of the bar, which restrict the elastic recovery of the die. The deflection drops sharply in the upper part of the die. This is due to the fact the elastic recovery of the die is complete in this area as there is no remaining bar material there. Higher COF, in general, results in higher die deflection in the region below the lower transition radius and lower die deflection in the remaining region. The maximum die deflection for COF 0.03 is 60.79 µm and for COF 0.05 the maximum die deflection is 65.33 µm with a very small difference of less than 5 µm.

Effect of Die Land Length

Die land length (DLL) of the die is the distance between the lower transition radii and the bottom of the die. DLL has a significant influence on the process of extrusion. The influence of change of DLL on extrusion process has been studied by considering the coefficient of friction as 0.04 and transition radii *R1* and *R2* as 10 mm. Results of finite element simulations to study the influence of DLL on punch force, component error and die deflection are presented in the following.

Effect of DLL on Punch Force

The punch force increases with the die land length though the increase is not linear as shown in Fig. 8.

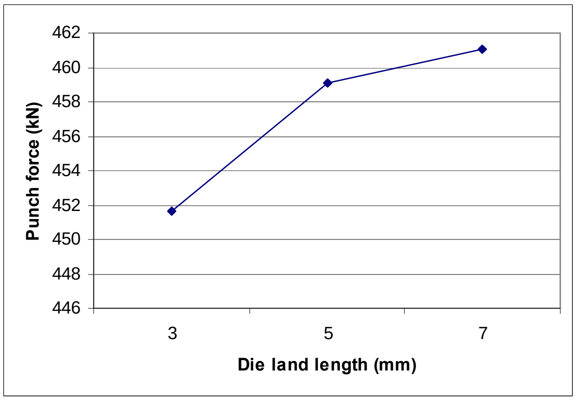

FIG. 8 EFFECT OF DLL ON PUNCH FORCE

Effect of DLL on Component Error

The component error at various locations is shown graphically in Fig. 9. The component error is practically constant for most of the extruded rod except for the initial portion and the portion near the die. The component error is too high for the initial portion of the extruded bar. It drops sharply near the portion in the die. It can be seen that the DLL has significant influence on the component error. The component error decreases by about 53.58 % when the DLL is increased from 3 mm to 7 mm.

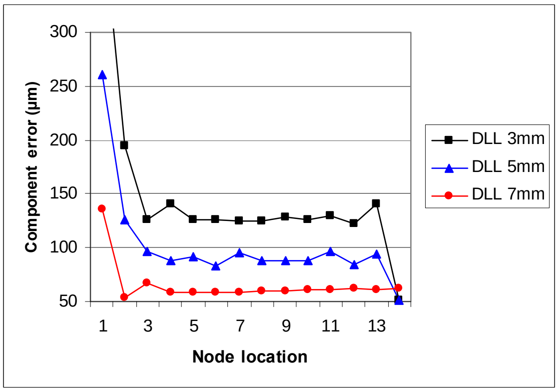

FIG. 9 EFFECT OF DLL ON COMPONENT ERROR

Higher DLL smoothen the flow of material as it emerges from the die. This, perhaps, contribute the lower component error. Lower bar temperature reduces the component error due to thermal contraction.

Effect of DLL on Die Deflection

The results of die deflection are shown graphically in Fig. 10.

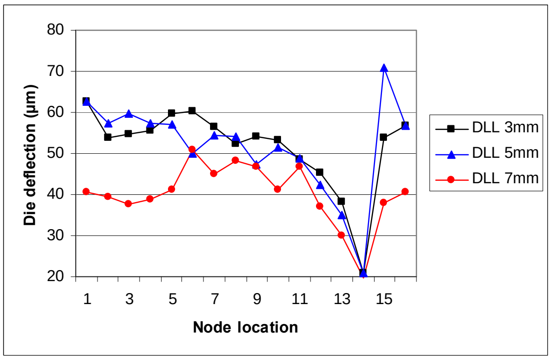

FIG. 10 EFFECT OF DLL ON DIE DEFLECTION

The die deflection decreases as the node location increases except for a portion around the lower transition radius where it increases sharply. The die deflection is more in the lower part of the die due to the presence of the bar, which restricts the elastic recovery of the die. The deflection drops sharply in the upper part of the die. This is due to the fact the elastic recovery of the die is complete in this area as there is no remaining bar material there. Increasing DLL from 3 mm to 5 mm increases the die deflection, slightly, whereas, further increase of DLL from 5 mm to 7 mm causes the die deflection to reduce. The die deflection at the exit of die for DLL 7 mm is very low (40.69 µm) in comparison to DLL 3 mm (62.76 µm).

Conclusions

The following conclusions can be drawn from the results of the FE simulation for establishing the contact, extrusion process, unloading and cooling of extruded material:

1. High level of the friction between billet and die generates the heat, which influences the elastic properties of billet and die. It leads to the increased deformation of the component and die during extrusion, the consequence being increased component-errors in the billet and deformation of the die. High levels of friction also prevent the relaxation of the billet from the die.

2. The radial dimension of the extruded material is less influenced by the transition contours between the planar sections of the billet and die, but it influences the unloading of the billet. Hence, it influences the component errors of the material which is contained in the die.

3. The elastic and plastic properties of the work-material and die-material are substantially influenced by the temperature variation due to various combinations of COF's and DLL's, during

extrusion and hence it influences the magnitude of the component-errors, which can be observed in the quality of the product. Billet material of higher yield strength and higher strain-hardening property may sustain higher component-errors at elevated temperature.

4. The geometric parameter of the tooling (die angle) increases the friction, hence will generate the heat and increase the process temperature, which influences the deflection of the die.

5. The die land length has significant effect on the component error which reduces with increased die land length. The die land length does not have significant effect on die deflection. It has a slight influence on die deflection.

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